

# SPECIALTY CHEMICALS AND ADVANCED MATERIALS FROM COALS: RESEARCH NEEDS AND OPPORTUNITIES

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1. Introduction

To use coals more efficiently as we move into the 21st century, it is important to explore the potentials and possible ways to develop high-value chemicals and materials from coals and coal liquids. This paper reports on our survey study, based mainly on literature and in part on our own experience. Our emphasis was placed on both the current status, including the applications and production level, and the future trends/growth rate of relevant chemicals and materials. The present study was guided by the following questions: What are the major problems and the future of industrial coal utilization? Is it necessary to develop coal chemicals now? What kinds of coal chemicals are more useful and competitive? Are there large-volume demands for coal chemicals? Is it really important to develop specialty chemicals and advanced materials? Are there large-volume applications of aromatic polymeric materials? How the aromatic specialty chemicals can be derived from coals and coal liquids? Are there new and better strategies for developing coal chemicals?

Discussed in this paper are 1) major problems facing the industrial utilization of coals such as carbonization, combustion and liquefaction, 2) the importance of developing coal chemicals, 3) new strategies for developing useful and competitive coal chemicals, and 4) some possible methods for developing several specialty chemicals such as 2,6-naphthalene dicarboxylic acid, and 5) some future research areas related to coal structural chemistry. Because units and pricing systems vary for different chemicals, both SI and English units are used but the conversion factors are given in appendix. Numerous abbreviations for long names were used, and they are listed in the appendix.

## 2. Worldwide Sources of Aromatic Chemicals

Petroleum and natural gas presently account for probably more than 90% of the organic chemicals [Sheldon, 1983; Speight, 1991]. They are the principal sources of the seven basic building blocks: ethylene, propylene, butadiene, benzene, toluene, xylenes and methanol. The principal sources of aromatic chemicals, however, include both petroleum and coal tar. About 3-4 % coal tars are produced as by-products from carbonization of coals in coke oven at about 1200 °C. In 1987 approximately 15-17 million tons (Mt) of coal tar and about 5 Mt of benzol were produced worldwide [Murakami, 1987; Mikami, 1988].

The annual consumption of aromatics in the world is about 25 Mt for BTX and 5 Mt for naphthalene, anthracene and other two- to four-ring aromatic compounds [Collin, 1985; Murakami, 1987]. About 95% of 2- to 4-ring polyaromatic and heterocyclic chemicals and about 15-25 % BTX chemicals come from coal tar (plus benzol) [Collin, 1985; Mikami, 1988]. In 1989, 7.5 Mt of coal tars were processed worldwide by distillation; about 950 thousand tons (Kt) naphthalene, 20 Kt anthracene, 10 Kt of methyl naphthalene, phenanthrene, acenaphthene, and pyrene were isolated for use in chemical industry; the remains were used as feedstocks for carbon blacks and for carbon materials [Kikuchi et al., 1989]. In Japan, about 2.5 Mt of coal tars are produced annually and 2 Mt tars are processed by distillation; and in Nippon Steel, about 0.6 Mt tars are processed annually [Okazaki and Nozaki, 1986]. With the rapidly growing engineering applications of aromatic polymer materials (Section 6), the demands for a number of 1-4 ring aromatic compounds will increase.

## 3. Current Status and Problems Facing Industrial Coal Utilization

Because of the 1990 Clean Air Act, switching of coal for combustion in electric utility boilers is expected and in the near future, more low rank coals, which have lower S and N contents, will be burned [Sondreal, 1991]. That humans are increasing the concentration of CO<sub>2</sub> in the atmosphere by burning fossil fuels, and the increased concern worldwide about global warming will certainly lead to pressure on use of all fossil fuels [Kasting, 1991]. Coal is by far the worst in terms of CO<sub>2</sub> production per unit energy production upon combustion. Coal is also a problem regarding NO<sub>x</sub>, SO<sub>x</sub>, and particulate emissions. It is likely that new laws will continue to mandate stricter controls on emissions of NO<sub>x</sub> and SO<sub>x</sub>, and in the near future, the control of CO<sub>2</sub> emission. Recent reserve estimates of natural gas suggest the reserve is much larger than heretofore thought. Natural gas produces half as much as CO<sub>2</sub> per J of energy as coal, and essentially no NO<sub>x</sub>, SO<sub>x</sub> or particulate. Thus natural gas is likely to be the fuel of choice for power generation in the future.

Another major industrial coal utilization is carbonization to produce metallurgical coke [Gray, 1989]. According to the data in 1987-1988, there are about 400 sets of coke ovens worldwide and approximately 450 Mt of bituminous caking coals are carbonized annually to produce about 350 Mt metallurgical coke (about 29 Mt in the USA in 1988); this coke production level account for the reduction of 800 Mt iron ores to produce approximately 450 Mt raw steel [Murakami, 1987; Patrick, 1991]. Coke production has been markedly reduced in recent years, and it appears this trend will continue. Reduced coke demand has come from reduced steel demand, which is largely due to competition from polymer materials, especially engineering plastics, and new technology of direct coal injection into blast-furnaces. By the end of 1989, 32 of Western Europe's 104 blast furnaces, and 23 out of 35 Japan's working blast furnaces were equipped for coal injection [Patrick, 1991].

It will become necessary to produce synthetic liquids from coals for transportation fuels and for chemicals. However, despite enormous strides in coal liquefaction research, and great effort at Wilsonville to reduce cost of coal-derived syncrudes, coal-derived liquid fuels are still not cost-effective with petroleum, and do not seem to be likely to compete with petroleum in near future. Moreover, the liquid fuels from coal must meet with the 1990 Clean Air Act Amendments. For this reason, the transportation fuels will be hydrogen-rich, highly aliphatic fuels. We need to realize that production of such fuels from coal-derived syncrudes will be considerably higher than those from petroleum crudes. This is because petroleum are originally aliphatic in nature, but coal-derived syncrudes are highly aromatic and contain primarily two- to four-ring polyaromatics; conversion to aliphatic transportation fuels would require extensive hydrotreating [Song et al., 1991a, 1991b].

#### 4. Importance and Opportunities for Developing Coal Chemicals and Materials

The question why it is necessary to develop chemicals and materials from coals may be answered with respect to what is happening in the world around coal. The overall picture of the situation that emerges from the above is as follows: Significantly reduced coke demand will reduce the demand for bituminous coking coals and substantially reduce the production of by-product coal tar. However, coal tars are the sources of most polyaromatic and heterocyclic chemicals, which are the chemicals of great interest as feedstocks for specialty chemicals and advanced materials (Sections 2 and 6), and currently coal tar pitch is the major raw materials for coal-based carbon fibers and other carbon materials (Section 8). The demands for aromatic chemicals, aromatic polymer materials, engineering plastics, carbon-fibers and other carbon materials are remarkable and are rapidly increasing. Increased environmental concern about the greenhouse effects will result in significant environmental pressure on the use of coals as boiler fuels. Abundant supplies of cheap and clean natural gas will compete with coal-fired power generation. Synthetic fuels from coals do not seem likely to be competitive with petroleum for transportation fuels until 2010 or beyond.

From this situation, it is clear that we now need to explore other ways of using coals. We need to recognize that, primarily, coal is a hydrocarbon source, and this apparently has been often overlooked. As a hydrocarbon source, coal can also be used as feedstock for chemicals and materials, in addition to its use as fuel. The 70's and 80's have brought an explosive developments and applications of various organic materials, and the 90's and 21st century will definitely see the significant growth of these materials including aromatic polymers such as engineering plastics, liquid crystalline polymers, and high-temperature heat-resistant polymers, polymer blends, polymer membranes, carbon fibers, carbon-plastic composite materials, and other carbon materials.

A major shift in emphasis of developing new polymer materials is taking place, from aliphatic polymers to the polymers with benzene ring in the chains, and from benzene ring to naphthalene ring or from benzene ring to biphenyl ring. The incorporation of aromatic ring structures has led to higher melting polymers. Future use of polymer materials will involve a significant shift to polymers with two-ring aromatic groups in the chain. These significant developments will give rise to large-volume industrial demands in the 90's and 21st century for a number of 1-4 ring aromatic chemicals and specialty chemicals (Sections 6-7) such as 2,6-dialkyl-naphthalene (2,6-DAN) and 4,4'-dialkylbiphenyl (4,4'-DAB), and high-quality pitch feedstocks for carbon fibers and other carbon materials.

By developing the critical chemicals and substances for the advanced materials, coal chemical research could contribute significantly to high-technology development. The commercial and military importance of advanced polymer materials such as liquid crystalline polymers (LCP) resides in their unique properties. However, their commercial future and availability is intimately tied to lowering their cost. In turn, this is largely determined by the cost of the aromatic monomers [NRC, 1990]. Many of the aromatic monomers for newly developed high-performance materials are not readily available from petroleum.

This situation provides an excellent opportunity for starting to explore the potentials and possible ways to develop high-value chemicals and materials from coals and coal liquids. The coal liquids-to-coal chemicals research can be viewed

as an extension of, or product development part, of coal liquefaction research. Development of high-value chemicals from coal liquids could not only increase significantly the economic viability of coal liquefaction process, but also make coal liquids more competitive with petroleum because the former contains many chemicals which are not found in the latter [Song et al., 1991a]. For example, W1-MD contains many two- to four-ring aromatics, which can be converted into high-value specialty chemicals (Section 7). Heavier coal liquids can be transformed to fuels, chemicals, and carbon materials. The direct coal-to-chemical conversion is a new concept (Section 5) and has not been studied. The ideal target of the direct coal-to-chemical conversion research is to allow the structural units in various coals be transformed directly to useful chemicals. Research toward this end will contribute greatly to exploring new coal chemistry.

## **5. Chemicals from Coals - Old but New Approach**

### **5.1 What Kinds of Chemicals from Coals ?**

Several decades ago, the change from acetylene to ethylene brought about an explosive change from coal-based chemical technology to petroleum technology. Petrochemical industry based on ethylene and propylene is still a major industry, and there is no need for coal to be competitive for producing the basic chemicals. Our idea on coal-to-chemicals is to develop more valuable aromatic chemicals from coals, including those which are not readily available from petroleum but will be needed in relatively large volumes, and those which can be obtained both from coal and petroleum such as BTX and phenolic compounds. The "aromatization" trend of materials development and applications described in Sections 6 and 7 strongly supports this idea. In this way, both petrochemicals and coal-chemicals can find their uses, and this will contribute to the highly efficient utilization of these valuable resources.

### **5.2 How to Derive Chemicals from Coal ?**

#### **5.2.1 Traditional Approaches**

The state-of-the-art of chemicals from coal has been reviewed recently by Schlossberg (1990). Among two general approaches to making chemicals from coal, in the first case, by-products such as carbonization tar could be subjected to some appropriate sequence of separation operations to produce eventually pure compounds of interest. The principal drawback is that the starting materials are often extremely complex mixtures. In tar from gasification of lignite, the most predominant compound type accounted for only 4.3% of one fraction. Thus, the sequence of separation steps needed to extract a particular compound becomes enormous. In the other approach, coal could be gasified to synthesis gas, the synthesis gas is converted via Fischer-Tropsch process to liquids, the liquids degraded to ethylene, and the ethylene used to synthesize desired chemical products. The technology for each of these processes is well known. Unfortunately, this route involves significant investment in plant equipment to manufacture what should ideally be a cheap commodity. Also, the overall procedure involves a degradation (gasification), followed by a synthesis (Fischer-Tropsch), followed by another degradation (cracking), followed by another synthesis (chemical manufacture). If one looks at the forest rather than the trees, this laborious tearing down and building up seems slightly crazy.

#### **5.2.2 New Approaches**

In regard to aromatic specialty chemicals, the liquids from advanced coal liquefaction, which retain mostly the original molecular components or ring structures of coals, may be theoretically more attractive as feedstocks for aromatic chemicals as compared to Fischer-Tropsch synthesis. This approach lead to aromatics, phenols, and heterocyclic compounds as chemicals. As compared to the distillate fractions of coal tars from coke oven which contain relatively simple and non-substituted aromatics, the disadvantage of chemicals from liquefaction is the presence of many, but not necessarily desirable, alkylsubstituents on the ring systems. Two approaches can be taken to overcome this problem. The first is to use a simple liquefaction method followed by catalytic dealkylation of the coal liquids. The second approach is catalytic or thermal liquefaction at lower temperature to derive the aromatic compounds, followed by thermal dealkylation via hydropyrolysis at higher temperature to take off the alkyl substituents, producing relatively simple aromatics. The key factors are the conversion efficiency and the product separation. These approaches may become promising with the large-volume demands for aromatic chemicals, and can be economically competitive if improved separation methods emerge.

All the above-mentioned methods can be viewed as "indirect" coal-to-chemical conversion. An alternative is to explore introducing a reagent into the coal to cleave only a certain well-defined set of bonds, carefully cutting out the structures of interest. It is generally thought that a significant number of the aromatic systems in low rank coals such as lignites and subbituminous coals contain only 1- to 2-ring. Low rank coals therefore offer promise for production of phenol and catechol type chemicals as well as BTX (benzene, toluene, xylenes) and naphthalene. A careful oxidation should be able to produce large yields of benzene carboxylic acids. If long chain aliphatic units exist, as some investigators believe, neatly clipping the ends of the aliphatic chains may allow useful materials based on aliphatic carbon to be recovered.

### **5.3 Supporting Research in Fundamental Coal Chemistry**

In the past ten years, there has been an accelerated development of our understanding of coal structures, reactivity, and reactions. What is needed more in order to assess the potential of this approach to chemicals from coals? First, more knowledge of the principal organic structural features is needed. Average parameters such as aromaticity are not very useful. To selectively obtain specialty chemicals, especially important knowledge is the number and specific position of substituents on aromatic rings in coals. When such knowledge is available, it should be possible to select specific coals and to select those types of bonds which are desired to cleave; and then knowledge is needed on the kinetics, mechanism, and the thermochemistry of the cleavage processes. Finally, better ways are needed of selecting appropriate solvents and adjusting the molecular size and polarity.

## 6. Aromatic Polymer Materials & Engineering Plastics Related to Coal Chemicals

We will review briefly the recent developments and applications of aromatic polymer materials and engineering plastic related to coal chemicals, namely, the polymers synthesized from aromatic monomers that can be made from coal and coal liquids. The world-wide consumption of synthetic polymers is now in the order of 70 Mt/yr, about 56% of which are plastics, 18% are fibers, and 11% synthetic rubber. The balance is made up of coatings and adhesives [Stevens, 1990]. The production of plastics is growing fast while the others are not. Assuming the industrial production indexes for synthetic polymer materials to be 100 in 1987, such indexes in 1990 are 115.8 for plastic materials, 92.7 for man-made fibers, and 88.6 for synthetic rubber [News-CI, 1991]. Numerous reviews on polymer materials have been published in recent years [Hall, 1981; Critchley et al., 1983; MacDermott, 1984; Bowden and Turner, 1987; Seymour, 1987; Stevens, 1990; Dyson, 1990; NRC, 1990; Weiss and Ober, 1990; Kroschwitz, 1991; Mark et al., 1992].

Engineering plastics are relatively higher in cost but have superior mechanical properties and greater durability, which make them competitive with metals, ceramics, and glass in a variety of applications. Engineering plastics is now a \$2 billion business in USA [Schlosberg, 1990]. More importantly, engineering plastics are rapidly growing market with consumption projected to increase up to 10% annually [Stevens, 1990]. The following are principal engineering plastics: polyamide / nylon (PA), polyacetal (PAL), polycarbonate (PC), polyphenylene oxides (PPO), thermoplastic polyester including polyethylene butylate (PBT) and polyethylene terephthalate (PET), polyarylate (PAR), polysulfone (PS), polyphenylene ether ether ketone (PEEK); and high-temperature heat-resistant polymers such as polyimides (PI) and polyamideimide (PAI). The top five are PA, PC, PPO, PAL, and PBT [Stevens, 1990]. The selling prices for the family of the 5 products was in the \$1.40-\$2.00 per pound (lb) range in 1985. It is forecast that consumption of thermoplastic polyester in North America will increase by 7.5% per year from 1.945 billion lb in 1990 to 2.79 billion lb in 1995, in which PET is the major player (from 1.73 to 3.425 billion lb) and the second is PBT (from 180 Mlb to 370 Mlb) [Vervain, 1991].

Polyimide-type heat-resistant polymers, as well as carbon fibers (Section 8) were developed initially for aerospace industry as better light-weight heat-resistant materials. They now have found wide commercial applications. Polyimides have experienced extremely rapid developments in recent years, the major emphasis being on engineering applications [Stevens, 1990].

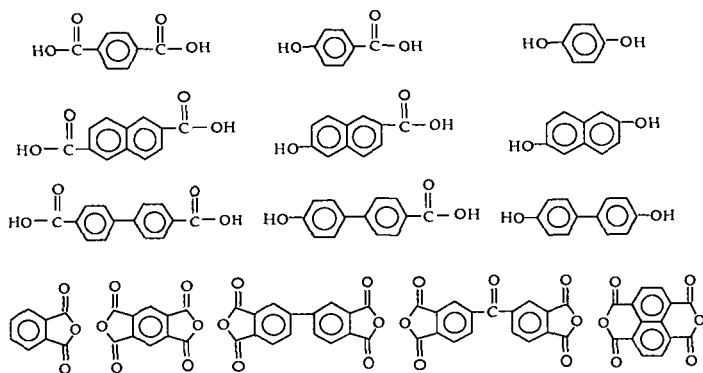
The liquid crystalline polymers (LCPs) containing naphthalene or biphenyl ring are capable of replacing metals and ceramics in many applications. Moldings of these rigid, rod-like, heat-resistant engineering polymers may be used in place of metals and ceramics for electronics, aerospace, and transportation applications [Seymour, 1987]. In 1989 worldwide production of LCP fibers is about 94 Mlb with an average market value of nearly \$10/lb; thermotropic LCPs about 10 Mlb (valued at about \$10/lb) of which about 5 Mlb was used in cookware [Weiss and Ober, 1990].

Most polymers are good insulators. However, some polymers such as poly-N-vinylcarbazole (PVCA) are photoconducting [Penwell et al., 1978]. Recently Hara and Toshima (1990) reported that the conductive and heat-resistant polymer films can be prepared by electrochemical polymerization of aromatic hydrocarbons such as naphthalene. Otani and co-workers reported that polyaromatics such as pyrene and phenanthrene can be used to make condensed polynuclear aromatics (COPNA) resin [Otani et al., 1986; Ota et al., 1988]. In addition, cyclic and short-chain linear phosphazenes with biphenyl as side chain [Allcock, 1991] may be viewed as biphenyl type organic-inorganic macromolecules.

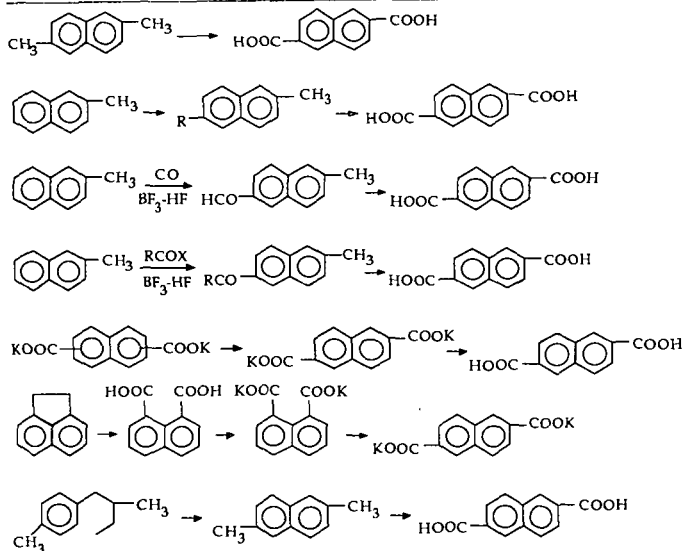
## 7. Monomers for High-Performance Polymers

Many aromatic and heteroatom-containing compounds can be converted into monomers for various polymers. Scheme 1 presents a list of important monomers for aromatic engineering plastics, liquid crystalline polymers (monomers in first 3 rows), and heat-resistant resins (monomers in the 4th row in Scheme 1). Because alkyl chains on aromatic rings can be readily oxidized to COOH or OH groups by using oxidizing agents or by heterogeneous catalytic oxidation, an

Scheme 1. Some Important Monomers for Aromatic Polymer Materials



Scheme 2. Possible Routes for Synthesis of 2,6-NDCA



important research subject is how to prepare the needed aromatics. For example, the oxidation of 2,6-DAN and 4,4'-DAB can readily give 2,6-naphthalene dicarboxylic acid (2,6-NDCA) and 4,4'-biphenyl dicarboxylic acid (4,4'-BDCA), respectively. Scheme 2 shows the possible routes for synthesis of 2,6-NDCA based on the chemicals that can be obtained from coal. By extending the methods used in catalytic synthesis of 1,4-xylene, terephthalic acid, and p-hydroxybenzoic acid, various methods seem to be available for the research and laboratory-scale synthesis of 2,6-disubstituted naphthalene and 4,4'-disubstituted biphenyl chemicals. However, because of the increase in the peripheral positions on the rings, the stereoselectivity is much more important, and in practice more difficult to control as compared to the situation of alkylbenzene.

Some of the coal-related important monomers for polyimides are pyromellitic anhydride (PMDA) and 1,4,5,8-naphthalene tetracarboxylic acid (NTCA) and its dianhydride (NTCADA) as well as the well known phthalic anhydride. Oxidation of pyrene produces NTCADA, which can be used for making some high-temperature heat-resistant resins. Phenanthrene and its derivatives are rich in coal-derived liquids, and can be obtained in relatively high yields from pyrolysis and carbonization tars. Considerable efforts have been devoted to finding the uses for it in the past decades, but its use is still very limited [Kurata, 1986]. During the Lewis acid-catalyzed hydrogenation of anthracene, sym-octahydrophenanthrene (sym-OHP) and phenanthrene were produced [Song et al., 1991c, 1989b]. sym-Octahydroanthracene (sym-OHA) was produced from phenanthrene over some acidic catalysts [Song et al., 1991 unpublished]. It is possible that sym-OHA can be formed from sym-OHP. Because sym-OHP can be obtained in considerably high yields by using supported NiW/Al<sub>2</sub>O<sub>3</sub> or NiMo/Al<sub>2</sub>O<sub>3</sub> catalysts [Shabtai, 1978; Song et al., 1988, 1991b; Ueda et al., 1990], it seems that one can hydrogenate phenanthrene and then isomerize sym-OHP to sym-OHA. The oxidation of sym-OHA and subsequent dehydration could produce PMDA, and dehydrogenation of sym-OHA can readily produce anthracene which is one of the most valuable chemicals and has found large-volume uses in dye industry as intermediate and in pulp industry as pulping agent (anthraquinone).

Biphenyl compounds are not as rich as naphthalene compounds in coal liquids. However, coal liquids contain phenanthrenes, fluorenes, dibenzofurans, and dibenzothiophenes. The latter three compounds can be converted to biphenyl type compounds by catalytic hydrocracking. Phenanthrene, may be used to produce diphenic acid and 4,4'-BDCA. Oxidation of phenanthrene can produce either phenanthraquinone or diphenic acid (biphenyl-2,2'-dicarboxylic acid). Diphenic acid may also be used for heat-resistant resins.

## 8. Advanced Carbon Materials from Coals and Coal Liquids

It is now well known that various useful carbon materials and composite materials can be made from coals, coal tars, coal liquids from liquefaction, and petroleum. It has been indicated in several recent reviews by Marsh [1989, 1991] and by Walker [1986, 1991] that the following are advanced or "old but new" carbon materials based on coal-derived feedstocks:

o Pitch-based carbon fibers	o Mesocarbon microbeads
o Mesophase-based carbon fibers	o Activated adsorbent carbons
o Carbon fiber reinforced plastic	o Activated carbon fibers
o Carbon whiskers or filament	o Metallurgical cokes
o Graphite and graphite-based materials	o Intercalation Materials
o Electrodes	o Fullerenes or bucky-balls
o Composite materials	o Diamond-like films
o Molecular sieving carbons	

Currently, coal tar pitch and bituminous coals (for making coke) are the major feedstocks of coal-based carbon materials. Coals ranging from low-rank coals to anthracites, and heavy liquids from coal liquefaction and tars from low temperature pyrolysis may be used for carbon materials in the future. The large-volume uses of coals for carbon materials can be stimulated significantly by the development of molecular sieving carbons (MSC) for gas separation and the adsorbent carbons for purifying water, air and medical and environmental applications. The application of MSC for air separation by PSA method is now commercially viable (Large-scale separation of CO from coal-derived gases may be carried out using COSORB method, provided care is taken to remove moisture and oxygen [Song et al., 1987, unpublished]). There are several recent review and original articles on coal-based carbon molecular sieves [Walker, 1986, 1990; Verma, 1991; Hashimoto, 1991] and adsorbent carbons [Marsh, 1989, 1991; Verheyen et al., 1991; Derbyshire and McEnaney, 1991a, 1991b].

The large-volume uses of coal liquids including those from carbonization and liquefaction may depend mainly on the development of technologies for producing general-purpose and mesophase-based carbon fibers, including activated carbon fibers for environmental protection uses, graphite electrodes, and mesophase microbeads-based materials. Several

reviews on carbon fibers are now available [Johnson 1989; Dorey, 1987; Anderson, 1987; Donnett, 1984]. Coal tar pitch-based carbon fibers are still in the development stage. Recently, commercialization of coal tar pitch carbon fibers has been announced by Mitsubishi Chemical (500 tons/yr) and Osaka Gas (300 tons/yr) through its subsidiary [Matsumura, 1989].

Coal-derived materials have higher N and O contents than petroleum feedstocks. Application of catalytic hydroprocessing for structural modification and heteroatom (especially N) removal of coal-derived carbonization feedstocks may become increasingly important for making mesophase-based carbon materials such as carbon fibers and graphite electrodes. Moderate hydrogenation and hydrodenitrogenation (HDN) of pitch feedstocks using large-pore [Song et al., 1991f, 1992f] hydrotreating catalysts can improve carbonization process; and perhaps more importantly, HDN of the feedstocks may significantly improve the properties of the coal-based mesophase carbon materials upon graphitization.

## 9. End of Beginning

Can we build a new basis in coal science for advanced and viable coal chemical industry? Would liquefaction of coals be commercialized in 21st century? Can we make break-through in coal-to-chemicals research to match the demands arising from rapidly developing polymer industry and carbon industry in the foreseeable future? Will it ever be possible to produce specific chemicals directly from coals? The future is not certain, particularly if the word "produce" carries the implication of a commercially viable process. Nevertheless, the potential exists, and the future may show handsome dividends from relatively modest investments in research on organic coal structures, reactivity, catalytic conversions, new pretreatments, novel reactions, supercritical extraction for the conversion processes such as direct coal-to-chemicals and coal liquids-to-chemicals tests coupled with advanced liquefaction method. While it may seem to be beyond the scope of "coal" science, the conversion of the coal aromatic chemicals to specialty chemicals such as 2,6-dialkyl-naphthalene is also important part, which determines the potential of coal chemicals as monomers for polymer materials.

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#### Abbreviations

BPL:	4,4'-Biphenol (p,p'-biphenol)
4,4'-BDCA:	4,4'-Biphenyl dicarboxylic acid
4,4'-DAB:	4,4'-Dialkylbiphenyl
2,6-DAN:	2,6-Dialkyl-naphthalene
ICI:	Imperial Chemical Industries
Lb:	Pounds (1 lb = 454 g)
LCP:	Liquid crystalline polymer
Kt:	Thousand tons (1 tons = 2204.6 pounds (lb))
Mlb:	Million pounds (1 Mlb = 453.59 tons)
MSC:	Molecular sieving carbon or CMS (carbon molecular sieves)
Mt:	Million tons (1 kg = 2.2046 lb)
2,6-NDCA:	2,6-Naphthalene dicarboxylic acid
sym-OHA:	1,2,3,4,5,6,7,8-Octahydroanthracene
sym-OHP:	1,2,3,4,5,6,7,8-Octahydrophenanthrene
PPO:	Polyphenylene oxide
PAR:	Polyarylate
PC:	Polycarbonate
PEEK:	Polyether ether ketone
PEN:	Polyethylene naphthalate
PET:	Polyethylene terephthalate
PBT:	Polybutylene terephthalate
p-HBA:	para-Hydroxy benzoic acid
PPTA:	Poly-p-phenylene terephthalamide (Du Pont's Kevlar LCP super-fibers)
PS:	Polysulfone
PSA:	Pressure-swing adsorption
PVCA:	Poly-N-vinylcarbazole
TPA:	Terephthalic acid
WI-MD:	Wilsonville middle distillates from catalytic two-stage coal liquefaction
3M:	Minnesota Mining and Manufacturing